

TRIGGERED STAR FORMATION AROUND MID-INFRARED BUBBLES IN G8.14+0.23 H II REGION

L. K. DEWANGAN¹, D. K. OJHA¹, B. G. ANANDARAO², S. K. GHOSH³, AND S. CHAKRABORTI¹

ABSTRACT

Mid-infrared (MIR) shells or bubbles around expanding H II regions have received much attention due to their ability to initiate a new generation of star formation. We present multi-wavelength observations around two bubbles associated with a southern massive star-forming (MSF) region G8.14+0.23, to investigate the triggered star formation signature on the edges of the bubbles by the expansion of the H II region. We have found observational signatures of the collected molecular and cold dust material along the bubbles and the ¹²CO(J=3-2) velocity map reveals that the molecular gas in the bubbles is physically associated around the G8.14+0.23 region. We have detected 244 young stellar objects (YSOs) in the region and about 37% of these YSOs occur in clusters. Interestingly, these YSO clusters are associated with the collected material on the edges of the bubbles. We have found good agreement between the dynamical age of the H II region and the kinematical time scale of bubbles (from the ¹²CO(J=3-2) line data) with the fragmentation time of the accumulated molecular materials to explain possible “collect-and-collapse” process around the G8.14+0.23 region. However, one can not entirely rule out the possibility of triggered star formation by compression of the pre-existing dense clumps by the shock wave. We have also found two massive embedded YSOs (about 10 and 22 M_⊙) which are associated with the dense fragmented clump at the interface of the bubbles. We conclude that the expansion of the H II region is also leading to the formation of these two young massive embedded YSOs in the G8.14+0.23 region.

Subject headings: dust, extinction – H II regions – ISM: bubbles – ISM: individual objects (IRAS 17599-2148) – stars: formation – stars: pre-main sequence

1. INTRODUCTION

Massive stars have a major impact on their surrounding environment due to their energetic wind, UV ionizing radiation and an expanding H II region (Zinnecker & Yorke 2007). In recent years, MIR shells or bubbles around the expanding H II regions have received much attention, because of their ability to initiate a new generation of star formation (Watson et al. 2008, 2009, 2010). Churchwell et al. (2006, 2007) identified about 600 such shells or bubbles based on a circular morphology in *Spitzer*-GLIMPSE 8 μm emission. It is now believed that such regions are very promising to observationally study the conditions of sequential/triggered star formation (Thompson et al. 2012, and references therein).

In this paper, we present a study of two MIR bubbles, CN107 and CN109, from the catalogue of Churchwell et al. (2007) around the G8.14+0.23 region. The G8.14+0.23 is an irregular Galactic ultra-compact (UC) H II region close to the IRAS 17599-2148 source, situated at a distance of 4.2 kpc (Kim & Koo 2001). The G8.14+0.23 region has been extensively studied in the radio, sub-mm and molecular line observations (Codella et al. 1994; Walsh et al. 1997, 1998; Kim & Koo 2001, 2003; Ojeda-May et al. 2002; Thompson et al. 2006). The region is ionized by an O6(B0) spectral class source and is also known as a bipolar blister type H II region due to a champagne flow (Kim & Koo 2001, 2003). The 6.7 GHz

Class II methanol maser (Walsh et al. 1997, 1998) and water maser (Codella et al. 1994) were also detected close to the IRAS position. The site of massive star formation is often associated with methanol and water maser emission. Kim & Koo (2001) found the velocity of ionized gas to be about 20.3 km s⁻¹ close to the IRAS position, using H76α recombination line profile. The velocity of molecular flow was obtained to be about 19.6 km s⁻¹ using CS J= 2-1 lines by Kim & Koo (2003). These velocities are close to the values obtained by NH₃(2,2) and (4,4) emissions to be about 19.3 km s⁻¹ (Churchwell et al. 1990) and 20.3 km s⁻¹ (Cesaroni et al. 1992), respectively. Kim & Koo (2003) found irregular morphology and clumpy structure of molecular cloud around G8.14+0.23, using ¹³CO (J= 1-0) and CS (J= 2-1) line intensity maps. Kim & Koo (2003) and Thompson et al. (2006) also found a molecular and dust emission ridge around the region. Okada et al. (2008) analyzed the MIR spectroscopic observations using *Spitzer*-Infrared Spectrograph (IRS) for 14 Galactic star-forming regions, including G8.14+0.23, in the wavelength range of 20 - 36.5 μm. They argued the presence of the shocked and ionized gas associated with the G8.14+0.23 region, based on the detection of [Si II], [Fe II] and [S III] emission lines and derived the abundance ratio of two ions against the solar abundance (*a_s*) as 0.060, 0.158 and 0.020 for (Fe⁺/Si⁺)_{as}, (Si⁺/S²⁺)_{as} and (Fe²⁺/S²⁺)_{as} respectively.

In recent years, multi-wavelength observations are utilized to trace out different components associated with the star-forming regions viz. ionized, shocked, cold dust and molecular gas, as well as embedded young stellar populations. In this paper, we present multi-wavelength observations to investigate the triggered star formation around the MIR bubbles associated with a southern MSF

Electronic address: lokeshd@tifr.res.in

¹ Department of Astronomy and Astrophysics, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400 005, India² Physical Research Laboratory, Navrangpura, Ahmedabad - 380 009, India³ National Centre for Radio Astrophysics, Ganeshkhind, Pune - 411 007, India

region G8.14+0.23. This region is not well explored in infrared wavelengths, especially the identification of embedded populations around the region. Our study also includes the search for the infrared counterpart(s) of embedded massive YSOs in their earlier phases and to understand their formation processes.

In Section 2, we introduce the archival data and data reduction procedures used for the present study. In Section 3, we examine the morphology of the G8.14+0.23 region in different wavelengths and the interaction of massive stars with its environment using various *Spitzer* MIR ratio maps. We also describe the selection of young population, their distribution around the G8.14+0.23 region and discuss the triggered star formation scenario on the edge of the bubbles in this section. In Section 4, we summarize our conclusions.

2. AVAILABLE DATA AROUND G8.14+0.23 AND DATA REDUCTION

Archival deep near-infrared (NIR) JHK_s images and catalogue of G8.14+0.23 region were obtained from the UKIDSS 6th archival data release (UKIDSSDR6plus) of the Galactic Plane Survey (GPS) (Lawrence et al. 2007). UKIDSS observations were made using the UKIRT Wide Field Camera (WFCAM; Casali et al. 2007) and fluxes were calibrated using Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006). The details of basic data reduction and calibration procedures are described in Dye et al. (2006) and Hodgkin et al. (2009), respectively. Magnitudes of bright stars ($J \leq 11.5$ mag, $H \leq 11.5$ mag and $K_s \leq 10.5$ mag) were obtained from the 2MASS, due to saturation of UKIDSS bright sources. Only those sources are selected for the study which have photometric magnitude error of 0.1 and less in each band.

We obtained narrow band molecular hydrogen (H₂; 2.12 μ m; 1 - 0 S(1)) imaging data from UWISH2 survey (Froebrich et al. 2011). We followed a similar procedure as described by Varricatt (2011) to obtain the final continuum-subtracted H₂ image using GPS K_s image.

The *Spitzer* Space Telescope Infrared Array Camera (IRAC (Ch1 (3.6 μ m), Ch2 (4.5 μ m), Ch3 (5.8 μ m) and Ch4 (8.0 μ m); Fazio et al. (2004)) and Multiband Imaging Photometer (MIPS (24 μ m); Rieke et al. (2004)) archival images were obtained around the G8.14+0.23 region from the ‘‘Galactic Legacy Infrared Mid-Plane Survey Extraordinaire’’ (GLIMPSE) and ‘‘A 24 and 70 Micron Survey of the Inner Galactic Disk with MIPS’’ (MIPSGAL) surveys. MIPSGAL 24 μ m image is saturated close to the IRAS 17599-2148 position. We performed aperture photometry on all the GLIMPSE images (plate scale of 0.6 arcsec/pixel) using a 2.4 arcsec aperture and a sky annulus from 2.4 to 7.3 arcsec using IRAF¹. The photometry is calibrated using zero magnitudes including aperture corrections, 18.5931 (Ch1), 18.0895 (Ch2), 17.4899 (Ch3) and 16.6997 (Ch4), obtained from IRAC Instrument Handbook (Version 1.0, February 2010).

We obtained 20 cm radio continuum map (resolution ~ 6 arcsec) from Very Large Array (VLA) Multi-Array Galactic Plane Imaging Survey (MAGPIS) (Helfand et al. 2006) to trace the ionized region around G8.14+0.23.

The molecular ¹²CO(J=3-2) (rest frequency 345.7959899 GHz) spectral line public processed archival data was also utilized in the present work. The CO observations were taken on 11 June 2009 at the 15 m James Clerk Maxwell Telescope (JCMT) using the HARP array. The JCMT archival reduced fits cube was used to extract the velocity information around the region using the Astronomical Image Processing System² (AIPS) package. The fits cube was loaded into AIPS and rotated to make the frequency axis the first one. An alternate velocity axis was defined from the frequency using the rest frame frequency of the CO J=3-2 transition. The data were Hanning smoothed over 476 m s⁻¹ to decrease the noise per channel. It was then integrated over the velocity range 10 to 30 km s⁻¹ to obtain the zeroth moment (column density), first moment (mean velocity) and second moment (velocity dispersion). Archival BOLOCAM 1.1 mm (Aguirre et al. 2011) and SCUBA 850 μ m (Di Francesco et al. 2008) images were also used in the present work. The effective FWHM Gaussian beam sizes of final 1.1 mm and 850 μ m images were 33 arcsec and 22.9 arcsec, respectively.

3. RESULTS AND DISCUSSION

3.1. Morphology of the G8.14+0.23 region in different wavelengths

Figure 1a represents the RGB color composite image using GLIMPSE (8.0 μ m (red) & 4.5 μ m (green)) and UKIDSS K_s (blue) of a region ($\sim 6.6 \times 5.9$ arcmin²) around G8.14+0.23. The 8 μ m band contains the two strongest polycyclic aromatic hydrocarbon (PAH) features at 7.7 μ m and 8.6 μ m, which are excited in the photodissociation region (or photon-dominated region, or PDR). The PDRs are the interface between neutral & molecular hydrogen and traced by PAH emissions. Figure 1b shows the 3 color composite image using UKIDSS J (blue), H (green) and K_s (red) band in log scale. The positions of IRAS 17599-2148 (★), UC H II region (◇), methanol maser (+) and water maser (×) are marked in the figure. The coordinates of UC H II region, methanol maser and water maser were taken from Kim & Koo (2001), Walsh et al. (1998) and Codella et al. (1994), respectively. Figure 1a displays the two extended MIR bubbles CN107 and CN109 prominently around the G8.14+0.23 region. It is to be noted that these bubble structures are not visible in any of the UKIDSS NIR images (see Figure 1b), but dark regions are seen corresponding to the bubble structures in Figure 1b. The two infrared sources (designated as IRS 1 and IRS 2) are seen close to the IRAS position and are also marked in Figure 1a (see subsection 3.3.1 for more details). Figure 2 shows color composite image made using MIPSGAL 24 μ m (red), GLIMPSE 8 μ m (green), and 3.6 μ m (blue) images, overlaid by BOLOCAM 1.1 mm and SCUBA 850 μ m emission by dotted white and solid yellow contours, respectively. MIPS 24 μ m image is saturated near to the IRAS position. MAGPIS 20 cm radio continuum emission is also overlaid in Figure 2 by black contours. The cold dust emission at 850 μ m is very dense and prominent at the interface of the two bubbles. It is to be noted that the peaks of cold dust and ionized gas are concentrated

¹ IRAF is distributed by the National Optical Astronomy Observatory, USA

² <http://www.aips.nrao.edu/>

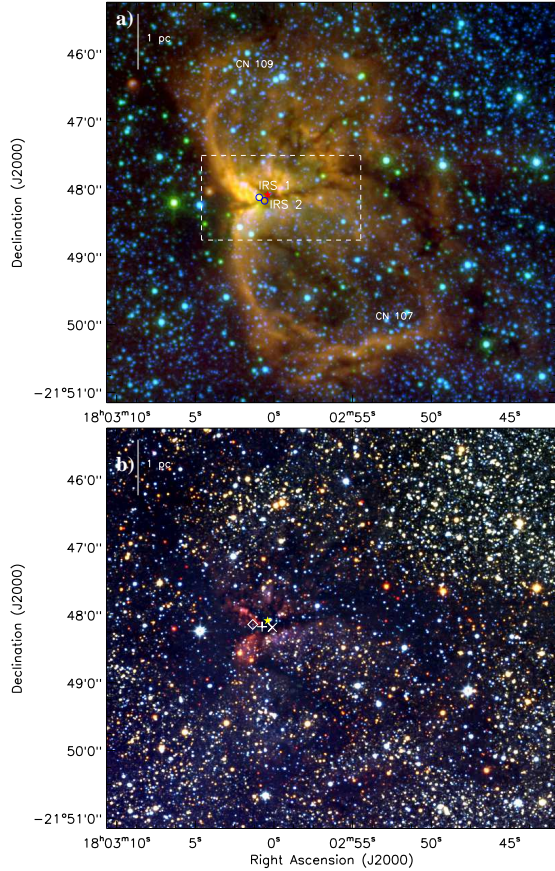


FIG. 1.— a) 3 color composite image (size $\sim 6.6 \times 5.9$ arcmin²; central coordinates: $\alpha_{2000} = 18^h 02^m 56^s.3$, $\delta_{2000} = -21^\circ 48' 12''.6$) of the G8.14+0.23 region, using *Spitzer*-GLIMPSE images at $8.0 \mu\text{m}$ (red), $4.5 \mu\text{m}$ (green) and UKIDSS K_s (blue) in log scale. The positions of the two sources (IRS 1 & IRS 2) are marked by blue circles and labeled on the image. The scale bar on the top left shows a size of 1 pc at the distance of 4.2 kpc. The white dashed box is shown as zoomed-in view in Fig. 8. Two bubbles from the Churchwell et al. (2007) are also labeled on the image as CN 107 and CN 109. b) Color composite image using UKIDSS J (blue), H (green) and K_s (red) in log scale. The positions of IRAS 17599-2148 (★), UC H II region (◇), methanol maser (+) and water maser (x) are marked in the figure.

near the IRAS position and interface of the bubbles. The $24 \mu\text{m}$ and 20 cm images trace the warm dust and ionized gas in the region, respectively. It is obvious from Figure 2 that the PDR region (traced by $8 \mu\text{m}$) encloses $24 \mu\text{m}$ and 20 cm radio emissions inside the bubbles and indicates the presence of dust in and around the H II region (see for example Watson et al. 2008, for N10, N21, and N49 bubbles).

3.2. IRAC Ratio Maps and the Collected material

In recent years, *Spitzer*-IRAC bands and ratio maps are utilized to study the interaction of massive stars with its immediate environment (Povich et al. 2007). The IRAC bands contain a number of prominent atomic and molecular lines/features such as H_2 lines in all channels (see Table 1 from Smith & Rosen 2005), $\text{Br}\alpha$ $4.05 \mu\text{m}$ (Ch2), FeII $5.34 \mu\text{m}$ (Ch3), ArII $6.99 \mu\text{m}$ and ArIII $8.99 \mu\text{m}$ (Ch4) (see Reach et al. 2006). It is to be noted that the *Spitzer*-IRAC bands, Ch1, Ch3 and Ch4, contain the PAH features at 3.3 , 6.2 , 7.7 and $8.6 \mu\text{m}$, whereas Ch2 ($4.5 \mu\text{m}$) does not include any PAH features. Therefore, IRAC ratio (Ch4/Ch2, Ch3/Ch2 and Ch1/Ch2) maps

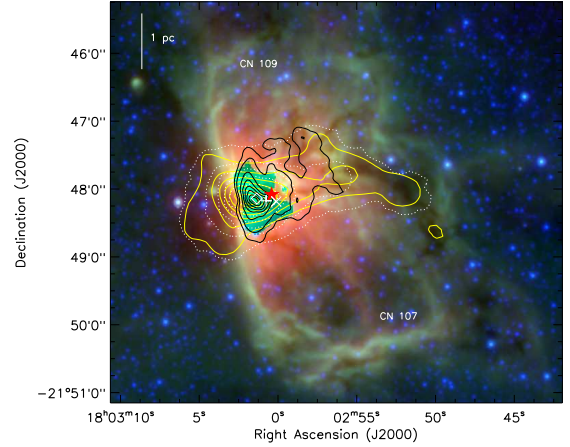


FIG. 2.— Figure represents 20 cm contours in black color around the G8.14+0.23 region obtained from the MAGPIS survey, overlaid on a color composite image made using the $24 \mu\text{m}$ (red), $8 \mu\text{m}$ (green), and $3.6 \mu\text{m}$ (blue) images. The 20 cm contour levels are 10, 25, 40, 55, 70, 85 and 95 % of the peak value i.e. 0.23 Jy/beam . BOLOCAM 1.1 mm and SCUBA $850 \mu\text{m}$ emissions are also shown by dotted white and solid yellow contours with 10, 25, 40, 55, 70, 85 and 95 % of the peak value i.e. 3.55 and 8.23 Jy/beam , respectively. Two bubbles from the Churchwell et al. (2007) are also labeled on the image as CN 107 and CN 109. The marked symbols are similar to as shown in Fig. 1 (see text for more details). MIPS $24 \mu\text{m}$ image is saturated near to the IRAS position.

are being used to trace out the PAH features in MSF regions (e.g. Povich et al. 2007; Watson et al. 2008; Kumar & Anandarao 2010) due to UV radiation from massive star(s). In order to make the ratio maps, we generate residual frames for each band removing point sources by choosing an extended aperture (12.2 arcsec) and a larger sky annulus ($14.6 - 24.4$ arcsec; Reach et al. 2005) in IRAF/DAOPHOT software (Stetson 1987). These residual frames are then subjected to median filtering with a width of 10 pixels and smoothing by 3×3 pixels using the boxcar algorithm (e.g. Povich et al. 2007). Figures 3a and 3b represent the IRAC ratio maps, Ch3/Ch2 and Ch4/Ch2 around the G8.14+0.23 region, respectively. The ratio contours are also overlaid on the ratio maps for better clarity and insight (see Fig. 3). Both the ratio maps clearly trace the prominent PAH emissions and subsequently extent of PDRs in the region.

Figure 4 shows the IRAC Ch2/Ch1 ratio map overlaid with Ch3/Ch2 ratio and MAGPIS 20 cm radio contours. The bright region traced by the Ch2/Ch1 ratio map is coincident with the 20 cm radio continuum emission, possibly due to presence of the $\text{Br}\alpha$ ($4.05 \mu\text{m}$) feature in Ch2 band around the H II region. One can also notice very faint diffuse emission along the edges of the bubbles away from the peak of 20 cm radio emission, possibly due to the molecular hydrogen feature in Ch2 band. Ojeda-May et al. (2002) detected two sources in the 6 cm radio observations around the G8.14+0.23 region. The positions of these sources are also shown in Figure 4. Figures 5a, 5b & 5c show the grey-scale images in SCUBA $850 \mu\text{m}$, BOLOCAM 1.1 mm and JCMT CO 3-2 (345.79599 GHz) around the G8.14+0.23 region respectively. Figure 5 exhibits the evidence of collected material along the bubbles traced by dust continuum (SCUBA $850 \mu\text{m}$ & BOLOCAM 1.1 mm) and molecular gas (JCMT CO 3-2 at 345.79599 GHz) emission, which is also indicated by red arrows. These arrows are

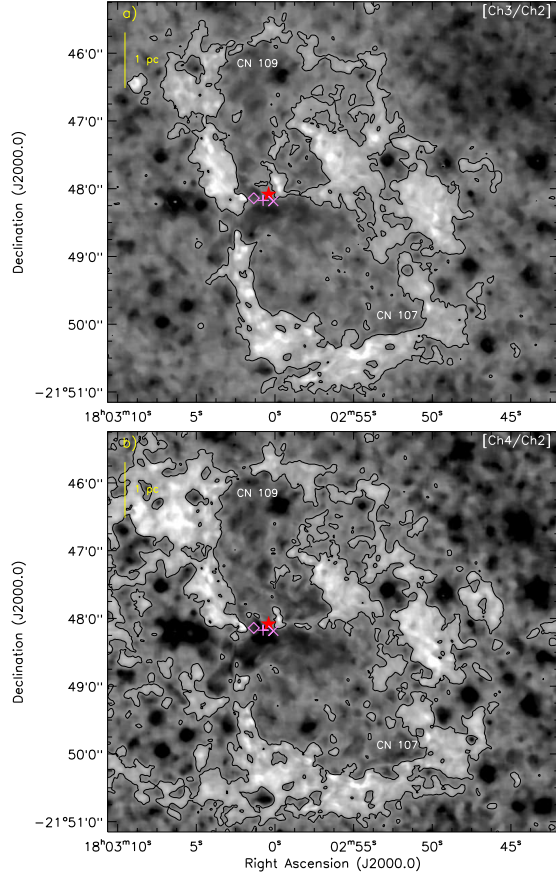


FIG. 3.— a) Figure exhibits the GLIMPSE Ch3/Ch2 ratio map of the G8.14+0.23 region (similar area as shown in Fig. 1). The ratio Ch3/Ch2 value is found to be “7–8” and “8.5–9” in the bubble interior and for the brightest part of the PDR respectively. The Ch3/Ch2 ratio contours are also overlaid on the image with a level of 7.7, a representative value between “7–8”. b) The Ch4/Ch2 ratio map of the region is shown here. The ratio Ch4/Ch2 value for the brightest part of the PDR and the interior is “30–34” and “23–25” respectively. The Ch4/Ch2 ratio contours are also overlaid on the image with a level of 24.8, a representative value between “23–25”. The marked symbols are similar to as shown in Fig. 1.

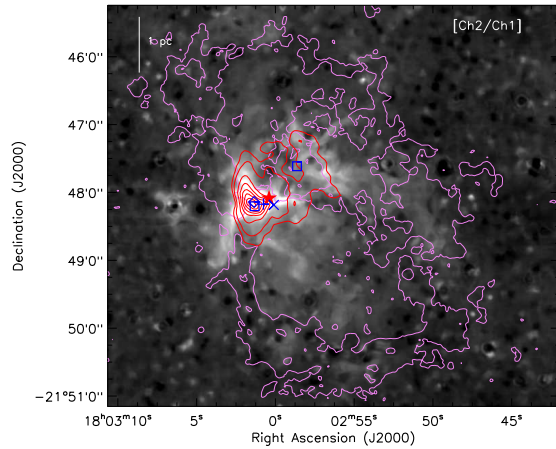


FIG. 4.— Figure exhibits the Ch2/Ch1 ratio image of the G8.14+0.23 region. The Ch3/Ch2 ratio contours in violet are also overlaid on the image with a level of 7.7. Contours in red color represent the 20 cm radio continuum emission with similar levels as shown in Fig. 2 around the region. Square symbols represent the 6 cm radio detections by Ojeda-May et al. (2002) and other marked symbols are similar to as shown in Fig. 1.

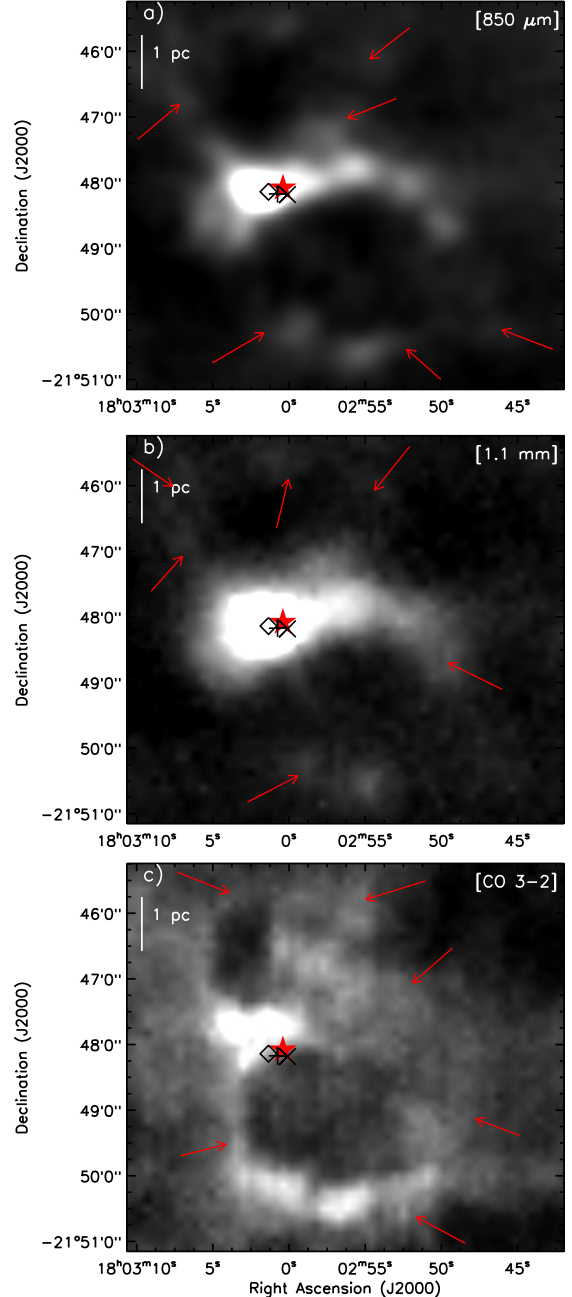


FIG. 5.— The grey-scale image in SCUBA 850 μm (a), BOLOCAM 1.1 mm (b) and JCMT CO 3-2 (c) around the G8.14+0.23 region, respectively. Red arrows show the detected faint features around the G8.14+0.23 region and other marked symbols are similar to as shown in Fig. 1.

marked to show the associated faint features above the 4-sigma noise level for each image. We further utilized JCMT public processed CO 3-2 cube data to observationally check the association of the molecular material with the expanding H II region seen as MIR bubbles. We calculated the mean H_2 number density near the H II region using ^{12}CO zeroth moment map. We derived the column density using the formula $N_{\text{H}_2} (\text{cm}^{-2}) = X \times W_{\text{CO}}$, where $X = 6 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{ s}$ (see Ji et al. 2012) and $W_{\text{CO}} = 48.08 \text{ K km s}^{-1}$ from our map. The mean H_2 number density is obtained to be 3575.7 cm^{-3}

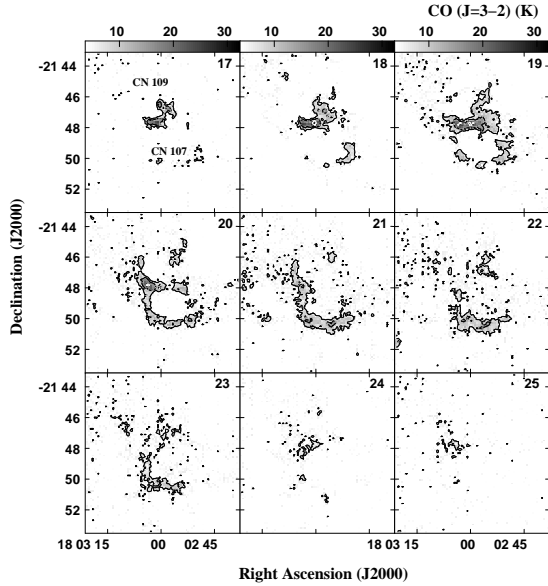


FIG. 6.— Figure shows the $^{12}\text{CO}(J=3-2)$ channel maps in 1 km s^{-1} steps with velocity interval between 17 to 25 km s^{-1} around the G8.14+0.23 region. The grey color scale bar at the top is presented in unit of K in the range of 4 to 32 K and the contours are plotted for 6.4, 12.8 and 25.7 K , from outer to inner side. The bubbles CN 107 and CN 109 are also labeled in the top left panel.

using the relation $N_{\text{H}_2} (\text{cm}^{-2})/L (\text{cm})$, where L is the molecular core size of about $8.07 \times 10^{18} \text{ cm}$ ($\sim 2.6 \text{ pc}$) near the H II region. Figure 6 exhibits molecular emission around the region between 17 and 25 km s^{-1} velocity interval in steps of 1 km s^{-1} . The bubbles (CN 107 and CN 109) are clearly traced by molecular emission in the velocity range of 19 to 21 km s^{-1} (see Fig. 6). We also estimated velocity dispersion of about 4 km s^{-1} (using second moment CO map) around the region, assuming a smooth rotation curve for the Galaxy with typical gas dispersion velocity of about 10 km s^{-1} (Stark & Brand 1989; Silk 1997). The consideration of velocity ranges of molecular gas in which bubbles are traced (see Fig. 6) and the velocity dispersion value, imply that the molecular gas in these bubbles are physically associated. These velocity ranges of molecular gas are also compatible with the ionized gas velocity ($\sim 20.3 \text{ km s}^{-1}$) obtained by the H76 α recombination line profile study around the H II region (Kim & Koo 2001), which shows the physical association of the molecular material and the H II region. The evidence of collected material along the bubbles is further confirmed by the detection of the H_2 emission (see Figure 7). Figure 7 represents the continuum-subtracted H_2 image at $2.12 \mu\text{m}$ and reveals that the H_2 emission surrounds the H II region along bubbles, forming a PDR region, which may be collected due to the shock. In brief, the PAH emission, cold dust emission, molecular CO gas and shocked H_2 emissions are coincident along the bubbles.

Figure 8 exhibits the zoomed-in color composite image using IRAC/GLIMPSE images (red: $8.0 \mu\text{m}$, green: $5.8 \mu\text{m}$ and blue: $4.5 \mu\text{m}$) around the G8.14+0.23 region. The slit positions of *Spitzer*-IRS spectrograph at 8 observed locations around the G8.14+0.23 region are also

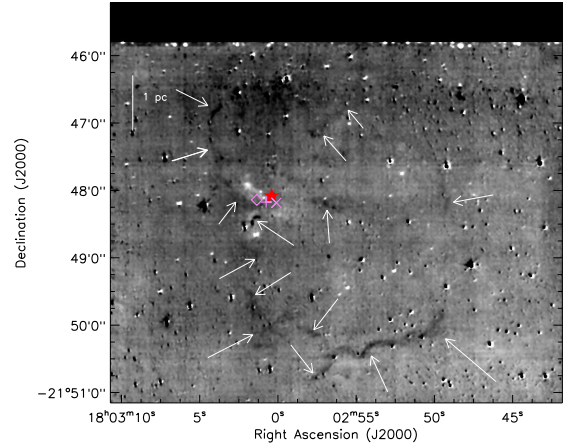


FIG. 7.— Figure represents the inverted grey-scale image of the continuum-subtracted H_2 image at $2.12 \mu\text{m}$. White arrows indicate the detected H_2 emission along the bubbles (as seen in GLIMPSE images) around the G8.14+0.23 region. The other marked symbols are similar to as shown in Fig. 1. The continuum-subtracted H_2 image is processed to median filtering with a width of 4 pixels and smoothed by 4×4 pixels using boxcar algorithm to trace out the faint features in the image.

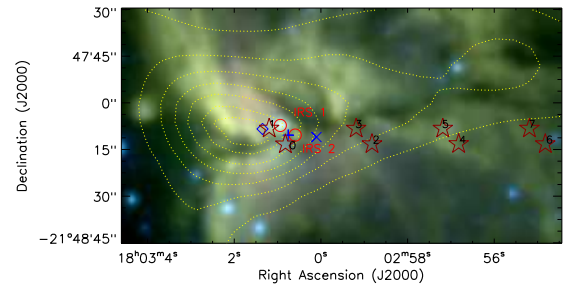


FIG. 8.— Zoomed-in 3 color composite image using IRAC $4.5 \mu\text{m}$ (blue), $5.8 \mu\text{m}$ (green) and $8.0 \mu\text{m}$ (red) around the G8.14+0.23 region (size $\sim 2.36 \times 1.26 \text{ arcmin}^2$; as shown by a dashed box in Fig. 1). Star symbols represent 8 positions of *Spitzer*-IRS slit around the G8.14+0.23 region and also labeled as 0 to 7. SCUBA $850 \mu\text{m}$ emission is also shown by dotted yellow contours with similar levels as shown in Fig. 2. The positions of IRS 1 & IRS 2 sources are marked by red circles and labeled in the image.

marked in the Figure 8 with star symbols (see Okada et al. 2008). Okada et al. (2008) also listed the line intensities of detected emission lines ([Ar III], $22 \mu\text{m}$; [Fe III], $23 \mu\text{m}$; [Fe II], $26 \mu\text{m}$; H_2 0-0 S(0), $28 \mu\text{m}$; [S III], $33 \mu\text{m}$; [Si II], $35 \mu\text{m}$ and [Ne III], $36 \mu\text{m}$) at the 8 observed positions (similar labels marked as 0 to 7 in Figure 8) around the G8.14+0.23 region. The presence of both PAH and fine structure line emissions around the region clearly suggest, the presence of an ionizing source with UV radiation close to radio and dust continuum peaks.

3.3. Photometric analysis of point-like sources around the G8.14+0.23 region

In order to trace ongoing star formation activity in the G8.14+0.23 region, we have identified YSOs using NIR and GLIMPSE data.

3.3.1. Identification of YSOs

We have used Gutermuth et al. (2009) criteria based on four IRAC bands to identify YSOs and various possible contaminants (e.g. broad-line AGNs, PAH-emitting galaxies, shocked emission blobs/knots and

PAH-emission-contaminated apertures). These YSOs are further classified into different evolutionary stages (i.e. Class I, Class II, Class III and photospheres) using slopes of the IRAC spectral energy distribution (SED). Fig. 9a shows the IRAC color-color ($[3.6]-[4.5]$ vs $[5.8]-[8.0]$) diagram for all the identified sources. We find 14 YSOs (6 Class 0/I; 8 Class II), 2 Class III, 123 photospheres and 8 contaminants in the G8.14+0.23 region. Two sources close to the peak of the dense molecular gas and the dust clump at the interface of the bubbles, IRS 1 and IRS 2, are also labeled in Fig. 9a. The position of IRS 2 is shown by a star symbol using $3.6 \mu\text{m}$ mag as an upper limit (see Table 1). It is to be noted that IRS 2 is close (about 2 arcsec) to the detected methanol maser. The details of the YSO classification can be found in Dewangan & Anandarao (2011). We have also applied criteria to identify YSOs as suggested by Hartmann et al. (2005) and Getman et al. (2007) for those sources that are detected in three IRAC/GLIMPSE bands, but not in the $8.0 \mu\text{m}$ band. We identify 12 more YSOs (2 Class 0/I; 10 Class II) through color-color diagram using three GLIMPSE bands in the region (see Fig. 9b).

UKIDSS NIR JHK_s photometry is used to identify more YSOs in the region. NIR color-color diagram (CC-D: H-K_s/J-H) is shown in Fig. 9c for all the sources detected in J, H and K_s bands. We have divided the CC diagram into three regions namely “F”, “T”, and “P” (e.g., Sugitani et al. 2002; Ojha et al. 2004a,b). The “F” sources are located between the reddening bands of the main-sequence and giant stars. The sources located within the “T” region along the T Tauri locus are T Tauri-like sources (Class II objects) with large NIR excess. “P” sources are those located in the region rearward of region “T”, and are most likely Class I objects (protostellar objects). We have identified 159 Class II and 30 Class I sources located in the “T” and “P” regions in the Fig. 9c, respectively. The identified Class I and Class II sources are shown by red circles and blue triangles in Fig. 9c. We have estimated the visual extinction (A_V) using the CC diagram and following the Indebetouw et al. (2005) extinction law, for those sources that fall within the “F” region (see Ojha et al. 2010). The average value comes out to be $A_V \sim 8.2 \text{ mag}$, which is in good agreement with that estimated ($A_V \sim 8.8 \text{ mag}$) by Rowles & Froebrich (2009) using 2MASS data for the G8.14+0.23 region.

GLIMPSE 3.6 and $4.5 \mu\text{m}$ bands are more sensitive for point sources than GLIMPSE 5.8 and $8.0 \mu\text{m}$ images. Therefore, a larger number of YSOs can be identified using a combination of NIR (JHK_s) with GLIMPSE 3.6 and $4.5 \mu\text{m}$ (i.e. NIR-IRAC) photometry, where sources are not detected in IRAC 5.8 and/or $8.0 \mu\text{m}$ band (Gutermuth et al. 2009). We followed the criteria given by Gutermuth et al. (2009) to identify YSOs using H, K_s, 3.6 and $4.5 \mu\text{m}$ data. We have found 29 more YSOs (26 Class II and 3 Class I) using NIR-IRAC data (see Fig. 9d).

Finally, we have obtained a total of 244 YSOs (203 Class II and 41 Class I) using NIR and GLIMPSE data in the region.

3.3.2. YSOs surface density map

To study the spatial distribution of YSOs, we generated the surface density map of all YSOs using a 5 arcsec

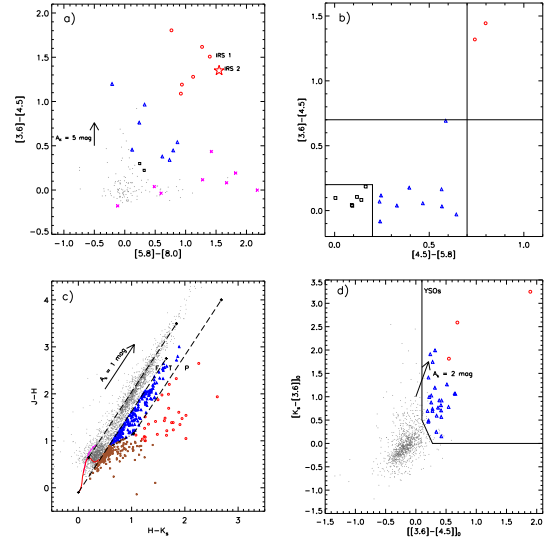


FIG. 9.— a) Color-color diagram (CC-D) using the *Spitzer*-IRAC four bands for all the sources identified within the region shown in Fig. 1. The extinction vector for $A_K = 5 \text{ mag}$ is shown by an arrow, using average extinction law from Flaherty et al. (2007). The dots in grey color around the centre (0,0) locate the stars with only photospheric emissions. The open squares (black), open triangles (blue) and open circles (red) represent Class III, Class II and Class 0/I sources respectively, classified using the α_{IRAC} criteria. The “x” symbols in magenta color show the identified PAH-emission-contaminated apertures in the region. The source IRS 2 is marked by a red star symbol and is also labeled along with the source IRS 1 in the diagram (see the text). b) CC-D of the sources detected in three IRAC/GLIMPSE bands, except $8.0 \mu\text{m}$. The open squares (black), open triangles (blue) and open circles (red) represent Class III, Class II and Class 0/I sources respectively, classified following the criteria suggested by Hartmann et al. (2005) and Getman et al. (2007). c) UKIDSS NIR (JHK_s) magnitudes are calibrated in 2MASS system. The unreddened dwarf and giants loci are shown by red and magenta curves (Bessell & Brett 1988) respectively. The long-dashed straight lines across the CC-D are the extinction vectors ($A_K = 3 \text{ mag}$) using Indebetouw et al. (2005) extinction law. The extinction vector $A_K = 1 \text{ mag}$ is also shown in the diagram. Classical T Tauri (CTTS) locus (in California Institute of Technology (CIT) system) (Meyer et al. 1997) is shown by a dashed-dotted line. The loci of unreddened dwarf (Bessell & Brett (BB) system), giant (BB-system) and CTTS (CIT system) are converted into 2MASS system using transformation equations given by Carpenter (2001). Red circles and open blue triangles represent the Class I and class II YSOs. The CC-D is classified into three regions namely “F”, “T”, and “P” (see text for details). d) Figure shows the de-reddened $[K_s - [3.6]]_0$ vs $[[3.6] - [4.5]]_0$ CC-D using NIR and GLIMPSE data. The selected region shown by the solid lines represents the location of YSOs. The extinction vector for $A_K = 2 \text{ mag}$ is shown by an arrow, calculated using the average extinction law from Flaherty et al. (2007). Open red circles and open blue triangles represent Class I and Class II sources respectively.

grid size, following the same procedure as given in Gutermuth et al. (2009). The surface density map of YSOs is constructed using 6 nearest-neighbour (NN) YSOs for each grid point. Fig. 10a shows the spatial distribution of all identified YSOs (Class I and Class II) in the region. The contours of YSO surface density and Ch3/Ch2 ratio map are also overlaid on the diagram. The levels of YSO surface density contours are 6 (2.5σ), 8 (3.3σ), 11 (4.6σ) and 16 (6.7σ) YSOs/ pc^2 , increasing from the outer to the inner region. We have also calculated the empirical cumulative distribution (ECD) as a function of NN distance to identify the clustered YSOs in the region. Using the ECD, we estimate the distance of inflection $d_c = 0.617 \text{ pc}$ (0.0084 degrees at 4.2 kpc) for the region for a surface density of 6 YSOs/ pc^2 (see Dewangan & Anandarao 2011, for details of d_c and ECD). We find

TABLE 1

NIR AND *Spitzer* IRAC/GLIMPSE PHOTOMETRIC MAGNITUDES ARE LISTED FOR SELECTED CLUSTERED YSOs HAVING LESS THAN OR EQUAL TO d_c VALUE CLOSE TO THE SUB-MM PEAK (SEE THE TEXT). SPECTRAL INDEX (α_{IRAC}) WAS OBTAINED BY FITTING OF IRAC WAVELENGTHS (SOURCES HAVING ATLEAST 3 IRAC WAVELENGTHS MAGNITUDE).

Source	RA[2000]	DEC[2000]	J (mag)	H (mag)	K_s (mag)	Ch1 (mag)	Ch2 (mag)	Ch3 (mag)	Ch4 (mag)	α_{IRAC}
IRS 1	18:03:00.94	-21:48:07.3	—	—	13.44±0.01	8.79±0.01	7.29±0.01	6.07±0.03	4.67±0.04	1.85
IRS 2	18:03:00.59	-21:48:10.5	—	—	—	≤ 11.78	10.39±0.10	7.68±0.05	6.13±0.07	3.96
IRS 3	18:03:00.36	-21:48:23.5	15.97±0.01	13.76±0.00	12.50±0.00	11.44±0.08	10.83±0.09	—	—	—
IRS 4	18:03:01.12	-21:48:01.9	16.63±0.02	14.98±0.01	13.54±0.01	11.10±0.14	9.43±0.10	—	—	—
IRS 5	18:03:02.90	-21:48:23.1	—	—	15.27±0.03	11.54±0.02	9.92±0.02	8.71±0.04	7.44±0.06	1.81
IRS 6	18:03:03.70	-21:48:45.8	17.94±0.05	15.87±0.02	14.51±0.01	13.14±0.05	12.59±0.07	—	—	—
IRS 7	18:03:04.33	-21:47:46.1	15.20±0.01	14.39±0.01	13.88±0.01	13.44±0.08	13.05±0.10	—	—	—
IRS 8	18:03:04.39	-21:48:31.1	—	—	15.72±0.04	11.27±0.01	9.47±0.01	8.55±0.01	7.79±0.02	1.03

that 37% (91 out of 244 YSOs) YSOs are present in clusters. Figure 10a reveals that the distribution of YSOs is mostly concentrated in the North and East regions, having peak density of about 20 YSOs/pc², while YSO density of about 8 (3 σ) YSOs/pc² is also seen around the West and South-East regions (see Figure 10a). These values of YSO surface density is much lower than usual values (about 30–60 YSOs/pc²) found in recent works (see Gutermuth et al. 2009, 2011) in MSF regions. Also the percentage of YSOs in clusters is low (only 37%) as compared to recent reports (about 60–80%) in MSF regions (see Gutermuth et al. 2009, 2011; Chavarria et al. 2008). It possibly supports the youth of the region and a site of further ongoing star formation. It is also to be noted that the YSO surface density is associated with the PDR region, on the edge of bubbles. The correlation of cold dust, molecular gas, ionized gas and YSO surface density is shown in Figure 10b. The association of YSOs with the collected materials around the region further reveals the ongoing star formation on the edge of bubbles. In addition, we have checked the possibility of intrinsically “red sources” contamination, such as AGB stars in our YSO sample. Recently, Robitaille et al. (2008) prepared an extensive catalogue of such red sources based on the *Spitzer* GLIMPSE and MIPS GAL surveys. They showed that two classes of sources are well separated in the [8.0 - 24.0] color space such that YSOs are redder than AGB stars in this space (see also Whitney et al. 2008). Since, MIPS 24 μ m data is saturated for the G8.14+0.23 region, we have therefore used criteria based on the IRAC magnitude (4.5 μ m) and color space ([4.5 - 8.0]), to estimate the AGB contamination. It is believed that the presence of AGB stars in the cluster is unlikely (see Dewangan & Anandarao 2011, and references therein). Therefore, we have applied red source criteria for only those YSOs which are cluster members with less than or equal to d_c value (see Fig. 10a). We find that GLIMPSE YSOs may be contaminated by AGB stars up to about 36% (5 out of 14 YSOs; see subsection 3.3.1).

3.3.3. SED modeling of clustered YSOs

In this subsection, we present SED modeling of some selected YSOs to derive their various physical parameters using an on-line SED modeling tool (Robitaille et al. 2006, 2007). Clustering analysis of identified YSOs reveals that there is a grouping of YSOs (~ 20 YSOs/pc²) close to the peak of the dense molecular gas and the dust clump in the region (see Fig. 10b). We have selected 8 YSOs (designated as IRS 1,...,IRS 8) from this cluster

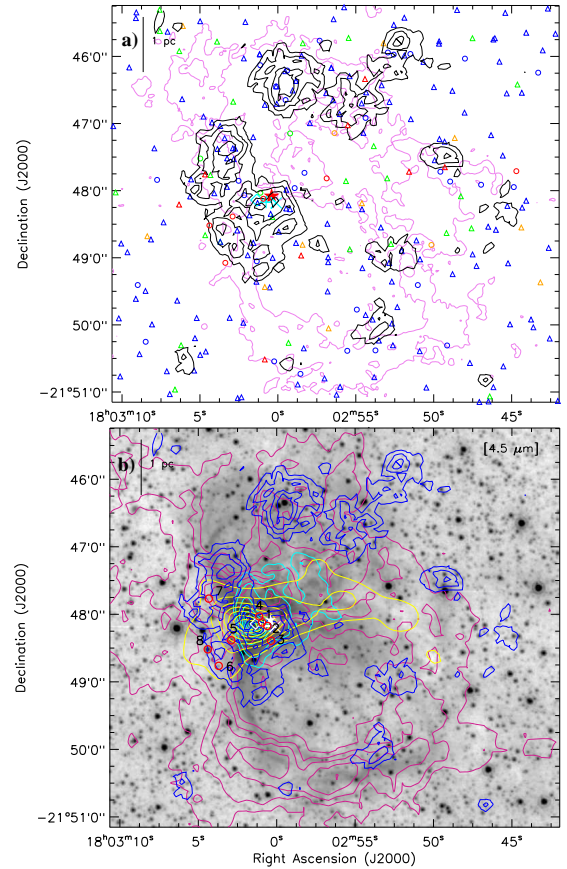


FIG. 10.— a) Figure represents the spatial distribution of all identified YSOs in the G8.14+0.23 region. The YSO surface density contours are plotted for 6, 8, 11 and 16 YSOs/pc², from outer to inner side (see text for details). The open circles and open triangles show the Class I and Class II sources respectively. The YSOs identified using four IRAC, three IRAC, NIR-IRAC and NIR data are shown by red, orange, green and blue colors respectively. The Ch3/Ch2 ratio contours in violet color are also overlaid on the image with a similar level as in Fig. 4 and other marked symbols are similar to as shown in Fig. 1. b) The schematic represents the spatial distribution of YSOs, dust emission, molecular gas and ionized gas in the G8.14+0.23 region. GLIMPSE 4.5 μ m image is overlaid with contours of YSO surface density (blue; similar levels as in Fig. 10a), SCUBA 850 μ m (yellow), MAGPIS 20 cm (cyan) and JCMT CO 3-2 (violet red) data. The CO 3-2 contour levels are 20, 29, 40, 55, 70 and 80 % of the peak i.e. 139.551 K km s⁻¹. The contour levels of SCUBA 850 μ m and MAGPIS 20 cm are similar to as shown in Fig. 2. The selected clustered YSOs (see subsection 3.3.3) are also marked (red circles) and labeled as 1,...,8 on the image (see Table 1).

close to the dense clump, which are detected atleast upto GLIMPSE 4.5 μm or longer wavelengths for SED modeling. NIR and *Spitzer* IRAC/GLIMPSE photometric magnitudes for these selected YSOs are listed in Table 1 along with IRAC spectral indices (α_{IRAC}) and are also labeled in Fig. 10b. IRAC spectral indices were calculated using a least squares fit to the IRAC flux points in a $\log(\lambda)$ versus $\log(\lambda F_\lambda)$ diagram for those sources that are detected in atleast 3 IRAC bands (see Dewangan & Anandarao 2011, for details). We have not included the MIPS 24 μm magnitude for SED modeling because the image is saturated close to the IRAS position. The SED model tool requires a minimum of three data points with good quality as well as the distance to the source and visual extinction value. A distance range of 3.7 to 4.7 kpc and the visual extinction in the range from 8 to 25 mag are used as input parameters in SED modeling tool for each source to constraint the SEDs. These models assume an accretion scenario with a central source associated with rotationally flattened infalling envelope, bipolar cavities, and a flared accretion disk, all under radiative equilibrium. The model grid consists of 20,000 models of two-dimensional Monte Carlo simulations of radiation transfer with 10 inclination angles, resulting in a total of 200,000 SED models. The grid of SED models covers the mass range from 0.1 to 50 M_\odot . Only those models are selected that satisfy the criterion $\chi^2 - \chi_{best}^2 < 3$, where χ^2 is taken per data point. The plots of SED fitted models are shown in Fig. 11 for all the selected sources. The weighted mean values of the physical parameters (age, mass, temperature, luminosity, envelope accretion rate (\dot{M}_{env}) and disk accretion rate (\dot{M}_{disk})) along with the standard deviations derived from the SED modeling for all the selected sources are given in Table 2. The table also contains the model-derived weighted mean values of A_V with standard deviations and the degeneracy of the models (i.e., the number of models that satisfy the χ^2 criterion as mentioned above). The derived SED model parameters show that the average value of mass, age and A_V of these clustered YSOs are about 7.8 M_\odot , 0.12 Myr and 15.5 mag, respectively. It is interesting to note that the embedded IRS 1 and IRS 2 sources are young and massive protostars. Finally, the SED modeling results favour the ongoing star formation around the region with detection of young YSOs as well as some massive candidates in their early phase of formation.

3.4. Star formation scenario

We have found evidence of collected material along the bubbles and also ongoing formation of YSOs on the edge of the bubbles. The morphology and distribution of YSOs suggest that the G8.14+0.23 region is a site of star formation possibly triggered by the expansion of the H II region. In recent years, the triggered star formation process, especially “collect and collapse” mechanism has been studied extensively on the edges of many H II regions such as Sh 2-104, RCW 79, Sh 2-212, RCW 120, Sh 2-217 (Deharveng et al. 2003, 2008, 2009; Zavagno et al. 2006, 2010; Brand et al. 2011). In order to check the “collect and collapse” process as triggering mechanism around the G8.14+0.23 region, we have calculated the dynamical age (t_{dyn}) of the H II region and compared it with an analytical model by Whitworth et al. (1994). We

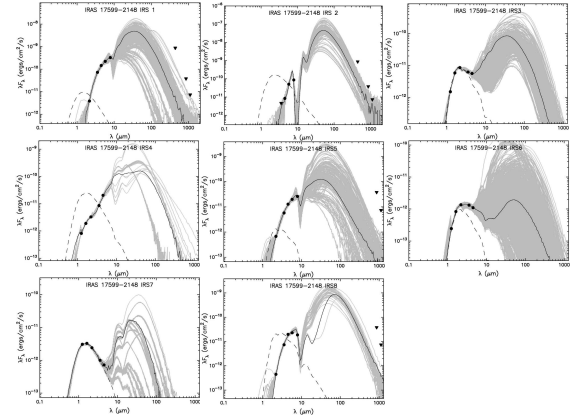


FIG. 11.— The SED plots of all the selected sources including IRS 1 & IRS 2 are shown here. Filled circles are observed fluxes of good quality (with filled triangles as upper limits) taken from the archives or published literature (see text for more details) and the curves show the fitted model with criteria $\chi^2 - \chi_{best}^2 < 3$. The thin black curve corresponds to the best fitting model. The dashed curves represent photospheric contributions.

have estimated the age of the H II region at a given radius R , using the following equation (Dyson & Williams 1980):

$$t_{dyn} = \left(\frac{4 R_s}{7 c_s} \right) \left[\left(\frac{R}{R_s} \right)^{7/4} - 1 \right] \quad (1)$$

where c_s is the isothermal sound velocity in the ionized gas ($c_s = 10 \text{ km s}^{-1}$) and R_s is the radius of the Strömgren sphere, given by $R_s = (3 N_{uv}/4\pi n_0^2 \alpha_B)^{1/3}$, where the radiative recombination coefficient $\alpha_B = 2.6 \times 10^{-13} (10^4 \text{ K}/T)^{0.7} \text{ cm}^3 \text{ s}^{-1}$ (Kwan 1997). In this calculation, we have used $\alpha_B = 3.9 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$ for the temperature of 5600 K (see Kim & Koo 2001). N_{uv} is the total number of ionizing photons per unit time, emitted by ionizing stars and “ n_0 ” is the initial particle number density of the ambient neutral gas. We have adopted the Lyman continuum photon flux value ($N_{uv} =$) of $1.2 \times 10^{49} \text{ ph s}^{-1}$ ($\log N_{uv} = 49.1$) from Kim & Koo (2001) for an electron temperature, distance and integrated 21 cm (1.43 GHz) flux density of 5600 K, 4.2 kpc, and 6.67 Jy respectively. We have estimated the ambient density ($n_0 =$) 3575.7 cm^{-3} of the H II region using $^{12}\text{CO}(J=3-2)$ line data (see subsection 3.2). Using N_{uv} , a mean radius of the H II region ($R =$) 5.9 pc (see Kim & Koo 2001), and $n_0 = 3575.7 \text{ cm}^{-3}$, we have obtained $t_{dyn} \sim 3.3 \text{ Myr}$ using Equation 1. Following, Whitworth et al. (1994) analytical model for the “collect and collapse” process, we have estimated a fragmentation time scale (t_{frag}) of 0.86 - 1.73 Myr for a turbulent velocity ($a_s =$) of 0.2 - 0.6 km s^{-1} in the collected layer. We have found that dynamical age is larger than fragmentation time scale for $n_0 = 3575.7 \text{ cm}^{-3}$. We have plotted the variation of t_{frag} and t_{dyn} with initial density (n_0) of the ambient neutral medium (see Fig. 12). The t_{frag} is also calculated for different turbulent velocities in Whitworth et al. (1994) model. It is to be noted that if t_{dyn} is larger than t_{frag} , then ambient density (n_0) should be larger than 900, 1500, 1700 and 1850 cm^{-3} for different “ a_s ” values of 0.2, 0.4, 0.5 and 0.6 km s^{-1} respectively (see Fig. 12). We have also estimated the kinematical time scale of molecular bubbles of about 1 Myr ($\sim 4 \text{ pc} / 4$

TABLE 2
PHYSICAL PARAMETERS DERIVED FROM SED MODELING OF THE SELECTED CLUSTERED YSOs (SEE THE TEXT).

Source Name	Age log(yr)	M_* (M_\odot)	T_* log(T(K))	L_* log(L_\odot)	\dot{M}_{env} log($M_\odot \text{ yr}^{-1}$)	\dot{M}_{disk} log($M_\odot \text{ yr}^{-1}$)	A_V (mag)	Degeneracy/ No. of models
IRS 1	5.17 \pm 0.72	10.33 \pm 2.11	4.23 \pm 0.26	3.74 \pm 0.26	-4.19 \pm 2.06	-6.96 \pm 1.28	19.55 \pm 5.47	316
IRS 2	3.86 \pm 0.24	22.40 \pm 2.61	4.01 \pm 0.16	4.49 \pm 0.20	-2.96 \pm 0.12	-5.97 \pm 0.51	17.63 \pm 2.48	158
IRS 3	4.92 \pm 0.37	3.51 \pm 1.07	3.66 \pm 0.03	1.88 \pm 0.18	-4.46 \pm 0.64	-7.70 \pm 1.09	13.19 \pm 2.08	821
IRS 4	5.46 \pm 0.86	6.75 \pm 2.53	4.11 \pm 0.26	3.13 \pm 0.56	-4.93 \pm 1.84	-8.77 \pm 2.71	13.63 \pm 3.85	40
IRS 5	4.50 \pm 1.09	5.01 \pm 2.40	3.79 \pm 0.27	2.53 \pm 0.45	-4.58 \pm 2.05	-6.36 \pm 1.38	19.49 \pm 5.13	376
IRS 6	5.73 \pm 0.55	2.47 \pm 0.97	3.69 \pm 0.09	1.24 \pm 0.29	-6.15 \pm 1.62	-8.49 \pm 1.68	14.12 \pm 2.12	3271
IRS 7	6.43 \pm 0.18	4.51 \pm 0.75	4.16 \pm 0.09	2.52 \pm 0.24	-7.90 \pm 0.17	-12.63 \pm 0.83	8.13 \pm 0.10	154
IRS 8	4.60 \pm 0.59	7.80 \pm 1.11	3.80 \pm 0.17	3.04 \pm 0.23	-3.61 \pm 0.31	-6.63 \pm 1.34	18.00 \pm 5.82	48

km s⁻¹), assuming bubble size of about 4 pc and velocity dispersion ~ 4 km s⁻¹ from ¹²CO(J=3-2) map (see subsection 3.2). The comparison of the dynamical age of the H II region and the kinematical time scale of expanding bubbles with the fragmentation time scale further supports triggered star formation and indicates the fragmentation of the molecular materials into clumps due to “collect and collapse” process around the bubbles. Further, the spatial distribution and the clustering analysis of YSOs show the association of YSO clusters in the North, East, West and South-East regions with molecular material along the bubbles. Among these, the average age of selected 8 YSOs, including IRS 1 and IRS 2 (see subsection 3.3.3), is about 0.12 Myr (estimated from SED modeling), which is less than the dynamical age of the H II region. We have also found that these two sources (IRS 1 and IRS 2) are young and massive embedded protostars (about 10 and 22 M_\odot) associated with the dense clump at the interface of the bubbles. It seems that the YSOs present on the edges of the bubbles are associated with the collected and fragmented molecular clumps, possibly by the “collect and collapse” process (see Kang et al. 2009; Pomares et al. 2009; Paron et al. 2011). This scenario is further supported by the detection of massive YSOs (IRS 1 and IRS 2) associated with the dense clump. However, one can not entirely rule out the possibility of triggered star formation by compression of the pre-existing dense clumps by the shock wave. It is therefore difficult to distinguish the star formation scenario from the pre-existing condensations and/or by the “collect and collapse” process in our selected region with the available data presented in this work.

Recently, Onaka et al. (2009) reported very broad emission features around 22 μ m in some MSF regions (viz., Cas A, Carina nebula and Sharpless 171) and suggested that this feature possibly originated from the dust grains formed in the supernova. Since the G8.14+0.23 region is about 0.3 degrees away from the W30 supernova remnant (SNR) and *Spitzer*-IRS spectroscopic observations are available for this region in the wavelength range of 20 – 36.5 μ m, it is possible to explore the signature of the supernova-induced star formation activity around this region. Following Onaka et al. (2009), we therefore re-examined the *Spitzer*-IRS processed archival spectra (AOR:14928896; PI: Yoko Okada) obtained from “*Spitzer* Heritage Archive³” around the G8.14+0.23 region (see IRS slit positions in Fig. 8 and also Okada et

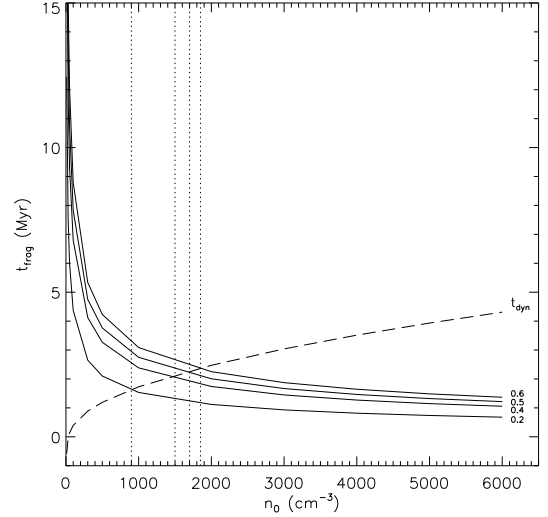


FIG. 12.— The schematic diagram shows the variation of fragmentation time scale (t_{frag}) and dynamical time (t_{dyn}) with initial density (n_0) of the ambient neutral medium. The fragmentation time scale is calculated for different turbulent velocity ($a_s = 0.2, 0.4, 0.5, \& 0.6$ km s⁻¹). Dotted black lines indicate the value of “ n_0 ” at which “ t_{dyn} ” is equal to “ t_{frag} ” for different “ a_s ” values.

al. 2008). We however did not find any broad feature around 22 μ m (see also Table 2 of Okada et al. 2008). Hence, we may reject the possibility of the supernova induced star formation activity in the G8.14+0.23 region. Ojeda-May et al. (2002) studied 9 MSF regions, including G8.14+0.23, in the vicinity of the W30 SNR using 6 cm radio observation and they also ruled out the possibility of a supernova induced star formation based on the 6 cm detection around this region and age consideration of the W30 SNR.

4. CONCLUSIONS

We have explored the triggered star formation scenario around two bubbles associated with a southern massive star forming region G8.14+0.23 using multi-wavelength observations. We find that there is a clear evidence of collected material (molecular and cold dust) along the bubbles around the G8.14+0.23 region. The JCMT CO velocity map reveals that the molecular gas in the bubbles is physically associated around the region G8.14+0.23. The surface density of YSOs reveals ongoing star formation and clustering of YSOs associated with the edge of the bubbles. We conclude that the YSOs are being formed on the edge of the bubbles possibly by the expansion of the H II region. We further investigated

³ see <http://irsa.ipac.caltech.edu/applications/Spitzer/SHA/>

the “collect-and-collapse” process for triggered star formation around the G8.14+0.23 region using analytical model of Whitworth et al. (1994). We have found that the dynamical age (~ 3.3 Myr) of the H II region is larger, and the kinematical time scale of bubbles (~ 1 Myr) is comparable to the fragmentation time scale ($\sim 0.86 - 1.73$ Myr) of accumulated gas layers in the region for 3575.7 cm^{-3} ambient density. The comparison of the dynamical age and the kinematical time scale of expanding bubbles with the fragmentation time scale further supports triggered star formation and indicates the fragmentation of the molecular materials into clumps possibly due to the “collect and collapse” process around the G8.14+0.23 region. We have also investigated infrared counterparts of two young massive embedded protostars (about 10 and $22 M_{\odot}$) associated with dense clumps at the interface of the bubbles. It seems that the expansion of the H II region is also leading to the formation of these two young massive embedded YSOs in the G8.14+0.23 region. Our study possibly favours the “collect and collapse” scenario for the formation of YSOs around the bubbles in the

G8.14+0.23 region. However, we can not entirely rule out the possibility of triggered star formation by compression of the pre-existing dense clumps by the shock wave.

We thank the anonymous referee for a critical reading of the paper and several useful comments and suggestions, which greatly improved the scientific content of the paper. This work is based on data obtained as part of the UKIRT Infrared Deep Sky Survey and UWISH2 survey. This publication made use of data products from the Two Micron All Sky Survey (a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center / California Institute of Technology, funded by NASA and NSF), archival data obtained with the *Spitzer* Space Telescope (operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA). We thank Dirk Froebrich for providing the narrow band H₂ image through UWISH2 survey.

REFERENCES

- Aguirre, J. E., Ginsburg, A. G., Dunham, M. K., et al. 2011, *ApJS*, 192, 4
- Bessell, M. S., & Brett J. M. 1988, *PASP*, 100, 1134
- Brand, J., Massi, F., Zavagno, A., Deharveng, L., & Lefloch, B. 2011, *A&A*, 527, 62
- Carpenter, J. M. 2001, *AJ*, 121, 2851
- Casali, M., Adamson, A., Alves de Oliveira, C., et al. 2007, *A&A*, 467, 777
- Cesaroni, R., Walmsley, C. M., & Churchwell, E. 1992, *A&A*, 256, 618
- Chavarría, L. A., Allen, L. E., Hora, J. L., et al. 2008, *ApJ*, 682, 445
- Churchwell, E., Walmsley, C. M., and Cesaroni, R. 1990, *A&AS*, 83, 119
- Churchwell, E., Povich, M. S., Allen, D., et al. 2006, *ApJ*, 649, 759
- Churchwell, E., Watson, D. F., Povich, M. S., et al. 2007, *ApJ*, 670, 428
- Codella, C., Felli, M., Natale, V., Palagi, F., & Palla, F. 1994, *A&A*, 291, 261
- Deharveng, L., Lefloch, B., Zavagno, A., et al. 2003, *A&A*, 408, L25
- Deharveng, L., Lefloch, B., Kurtz, S., et al. 2008, *A&A*, 482, 585
- Deharveng, L., Zavagno A., Schuller, F., et al. 2009, *A&A*, 496, 177
- Dewangan, L. K., & Anandarao, B. G 2011, *MNRAS*, 414, 1526
- Di Francesco, J., Johnstone, D., Kirk, H., MacKenzie, T., & Ledwosinska, E. 2008, *ApJS*, 175, 277
- Dye, S., Warren, S. J., Hambly, N. C., et al. 2006, *MNRAS*, 372, 1227
- Dyson, J. E., & Williams, D. A. 1980, *Physics of the interstellar medium*, New York, Halsted Press, 204 p
- Fazio, G. G., Hora, J. L., Allen, L. E., et al. 2004, *ApJS*, 154, 10
- Flaherty, K. M., Pipher, J. L., Megeath, S. T., et al. 2007, *ApJ*, 663, 1069
- Froebich, D., Davis, C. J., Ioannidis, G., et al. 2011, *MNRAS*, 413, 480
- Getman, K. V., Feigelson, E. D., Garmire, G., Broos, P., & Wang, J. 2007, *ApJ*, 654, 316
- Gutermuth, R. A., Megeath, S. T., Myers, P. C., et al. 2009, *ApJS*, 184, 18
- Gutermuth, R. A., Pipher, J. L., Megeath, S. T., et al. 2011, *ApJ*, 739, 84
- Hartmann, L., Megeath, S. T., Allen, L., et al. 2005, *ApJ*, 629, 881
- Helfand, D. J., Becker, R. H., White, R. L., Fallon, A., & Tuttle, S. 2006, *AJ*, 131, 2525
- Hodgkin, S. T., Irwin, M. J., Hewett, P. C., & Warren, S. J. 2009, *MNRAS*, 394, 675
- Indebetouw, R., Mathis, J. S., Babler, B. L., et al. 2005, *ApJ*, 619, 931
- Ji, W.-G., Zhou, J.-J., Esimbek, J., et al. 2012, *arXiv:1206.2762v1*
- Kang, M., Bieging, J. H., Kulesa, C. A., & Lee, Y. 2009, *ApJ*, 701, 454
- Kim, K. T., & Koo, B. C 2001, *ApJ*, 549, 979
- Kim, K. T., & Koo, B. C 2003, *ApJ*, 596, 362
- Kumar, Dewangan Lokesh, & Anandarao, B. G. 2010, *MNRAS*, 407, 1170
- Kwan, J. 1997, *ApJ*, 489, 284
- Lawrence, A., Warren, S. J., Almaini, O., et al. 2007, *MNRAS*, 379, 1599
- Meyer, M. R., Calvet, N., & Hillenbrand, L. A. 1997, *AJ*, 114, 288
- Ojeda-May, P., Kurtz, S. E., Rodríguez, L. F., Arthur, S. J., & Velázquez, P. 2002, *RMxAA*, 38, 111
- Ojha, D. K., Tamura, M., Nakajima, Y., et al. 2004a, *ApJ*, 608, 797
- Ojha, D. K., Tamura, M., Nakajima, Y., et al. 2004b, *ApJ*, 616, 1042
- Ojha, D. K., Kumar, M. S. N., Davis, C. J., & Grave, J. M. C. 2010, *MNRAS*, 407, 1807
- Okada, Y., Onaka, T., Miyata, T., et al. 2008, *ApJ*, 682, 416
- Onaka, T., Roellig, T. L., Okada, Y., & Chan, K. W. 2009, *eimw.confE*, 11 (Fourth Spitzer Conference, Pasadena, CA, Dec., 2-5, 2007)
- Paron, S., Petriella, A., & Ortega, M. E. 2011, *A&A*, 525, 132
- Pomarés, M., Zavagno, A., Deharveng, L., et al. 2009, *A&A*, 494, 987
- Povich, M. S., Stone, J. M., Churchwell, E., et al. 2007, *ApJ*, 660, 346
- Reach, W. T., Megeath, S. T., Cohen, M., et al. 2005, *PASP*, 117, 978
- Reach, W. T., Rho, J., Tappe, A., et al. 2006, *AJ*, 131, 1479
- Rieke, G. H., Young, E. T., Engelbracht, C. W., et al. 2004, *ApJS*, 154, 25
- Robitaille, T. P., Whitney, B. A., Indebetouw, R., Wood, K., & Denzmore, P. 2006, *ApJS*, 167, 256
- Robitaille, T. P., Whitney, B. A., Indebetouw, R., & Wood, K. 2007, *ApJS*, 169, 328
- Robitaille, T. P., Meade, M. R., Babler, B. L., et al. 2008, *AJ*, 136, 2413
- Rowles, J., & Froebich, D. 2009, *MNRAS*, 395, 1640
- Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, *AJ*, 131, 1163
- Stark, A. A. & Brand, J. 1989, *ApJ*, 339, 763
- Silk, J. 1997, *ApJ*, 481, 703
- Smith, M. D., & Rosen, A. 2005, *MNRAS*, 357, 1370
- Stetson, P. B. 1987, *PASP*, 99, 191

- Sugitani, K., Tamura, M., Nakajima, Y., et al. 2002, *ApJ*, 565, L25
- Thompson, M. A., Hatchell, J., Walsh, A. J., MacDonald, G. H., & Millar, T. J. 2006, *A&A*, 453, 1003
- Thompson, M. A., Urquhart, J. S., Moore, T. J. T., & Morgan, L. K. 2012, *MNRAS*, 421, 408
- Varricatt, W. P. 2011, *A&A*, 527, 97
- Walsh, A. J., Hyland, A. R., Robinson, G., & Burton, M. G. 1997, *MNRAS*, 291, 261
- Walsh, A. J., Burton, M. G., Hyland, A. R., & Robinson, G. 1998, *MNRAS*, 301, 640
- Watson, C., Povich, M. S., Churchwell, E. B., et al. 2008, *ApJ*, 681, 1341
- Watson, C., Corn, T., Churchwell, E. B., et al. 2009, *ApJ*, 694, 546
- Watson, C., Hanspal, U., & Mengistu, A. 2010, *ApJ*, 716, 1478
- Whitworth, A. P., Bhattal, A. S., Chapman, S. J., Disney, M. J., & Turner, J. A. 1994, *MNRAS*, 268, 291
- Whitney, B. A., Sewilo, M., Indebetouw, R., et al. 2008, *AJ*, 136, 18
- Zavagno, A., Deharveng, L., Comeron, F., et al. 2006, *A&A*, 446, 171
- Zavagno, A., Russeil, D., Motte, F., et al. 2010, *A&A*, 518, L81
- Zinnecker, H., & Yorke, H. W. 2007, *ARA&A*, 45, 481